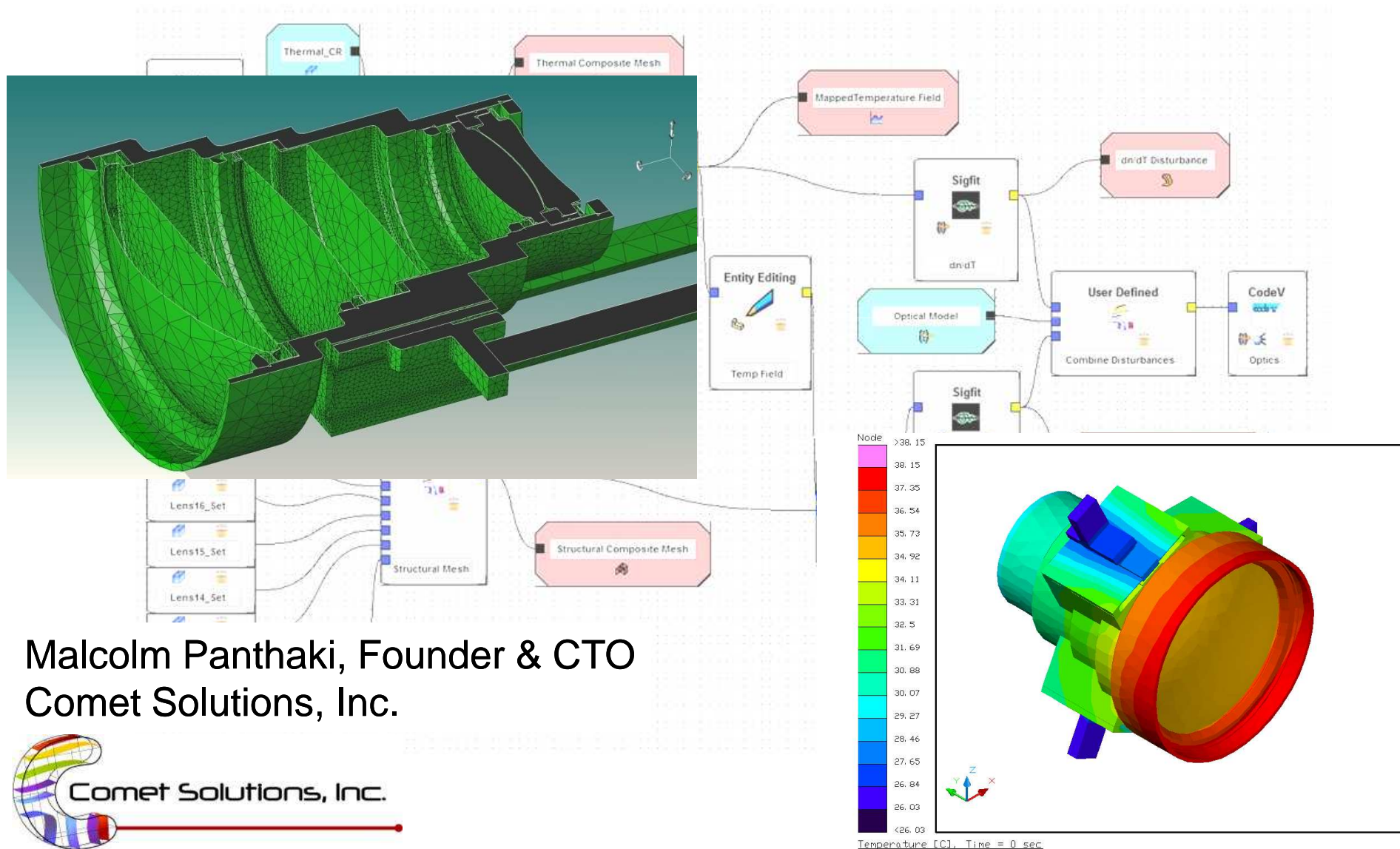


Collaborative Electro-Optics Sensor Design using a Performance Engineering Workspace



Malcolm Panthaki, Founder & CTO
Comet Solutions, Inc.

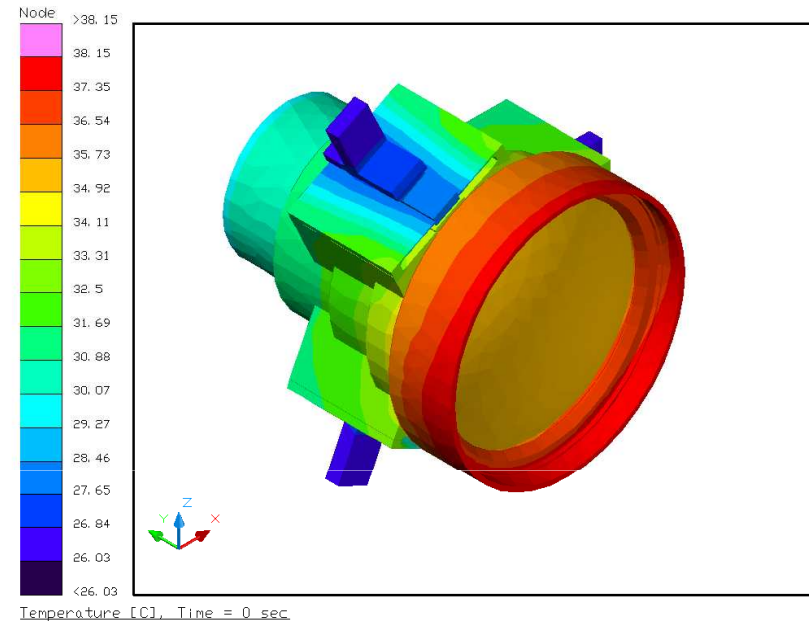


Agenda

- The importance of Systems Engineering
- Concurrent Engineering as an effective approach to integrated product design and systems engineering
- Enabling integrated product design – The Comet Performance Engineering Workspace
- A Case Study:
Seamlessly integrated Structural/ Thermal/Optical (STOP) analysis using the Comet Workspace
- Conclusions

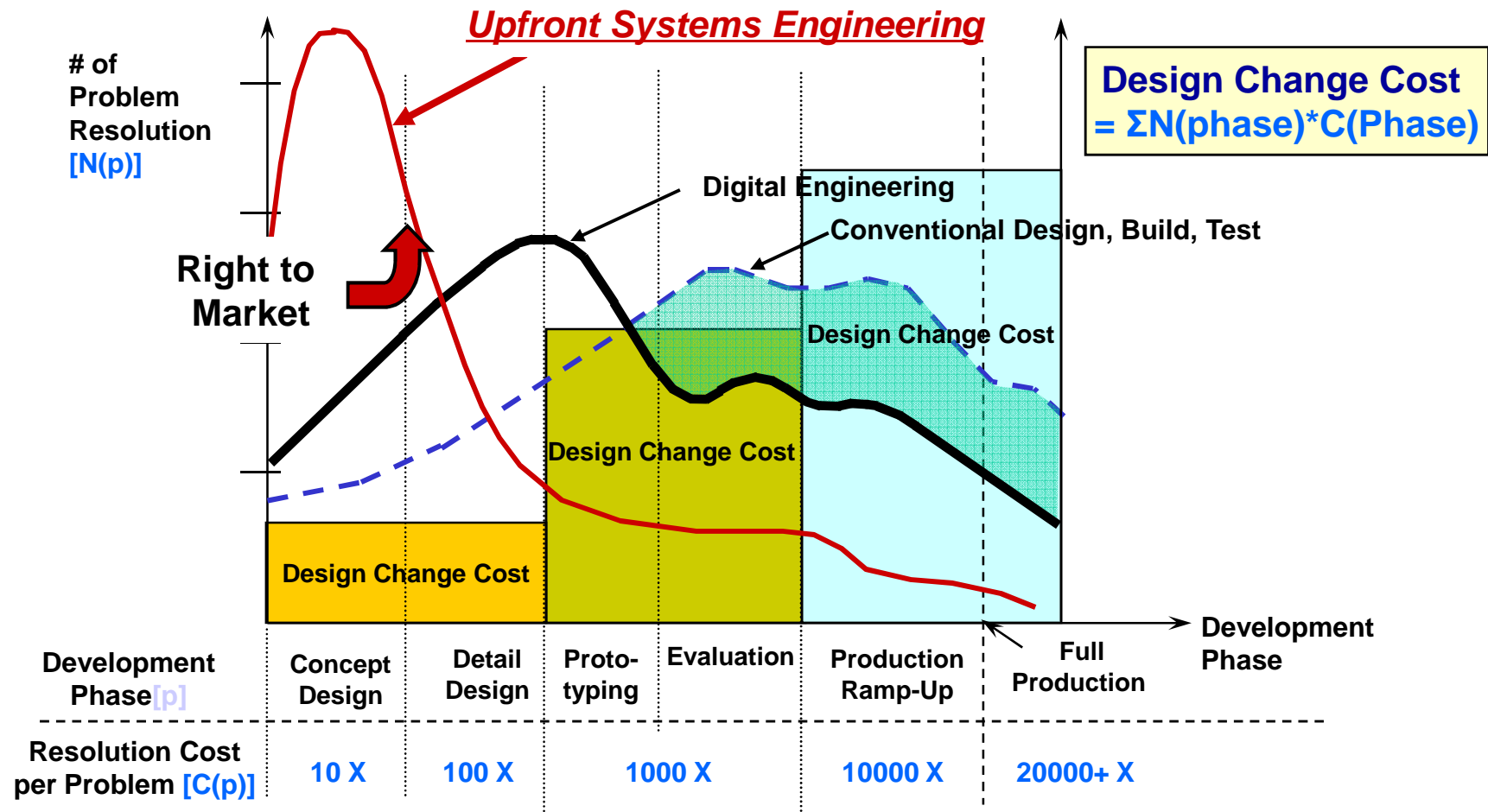
What Is STOP Analysis?

- STOP analysis is the evaluation of optical performance impacts caused by structural and refractive index changes in a space-borne Electro-Optical sensor that are produced by quasi-static changes in its thermal environment as it goes through its orbit.
- The process typically involves multi-disciplinary issues and multiple domain experts working with multiple CAD and CAE tools in multiple “silos”.



“Upfront Systems Engineering” Pays Off

Right to Market = Time To Market, Cost, Reliability & Quality



So Why Not Do It? *Barriers to Upfront SE*

- **Digital Engineering/Simulation – the exclusive domain of experts**
 - Narrow simulation experts: *particular* physics and *particular* codes
 - **Silos** of experts, tools and data
 - Years to develop experts: limited, expensive human resources
 - Systems analysis takes too long to complete: becomes the bottleneck and gets “left behind”; product teams depend more on testing
- **System Performance – hard to obtain the data early**
 - **Silos** inhibit a concurrent engineering approach, a full systems view
 - **Silos** inhibit exploring multiple concepts at higher fidelity early
 - **Silos** make it highly inefficient to view Key Performance Indicators: design reviews are ineffective and inefficient, using static presentations
 - **Silos** inhibit cascading requirements: analysis should drive design, comparing system performance against requirements
- **Chasm between Concept and Detailed Phases**
 - Different experts, tools and data: cannot mix levels of fidelity
 - No easy iterative flow of data between the phases: loop-back issues
 - *Tyranny of CAD*: not created for analysis, huge waste of time “preparing CAD for analysis”, all analysis data attached to CAD and changes to the CAD requires a ton of rework for downstream analysis

Chasm Between Concept and Detailed Design Phases

- *Lower Fidelity Trade Studies*
- *0 -1D math models, design handbooks and empirical rules based on experience*
- *Typically no detailed CAD geometry*

- *High Fidelity Design Validation*
- *Detailed 3-D math models & prototypes*
- *Typically tied to 3-D CAD geometry*
- *Multi-physics simulations but often still sequential across domain silos*

Business Portfolio/
Product Planning

System Level
Performance
Requirements

Detailed Engineering
Requirements/QFD

Design Concept
Exploration

High Level System
Design

Detailed CAD
Design

Linking the
Systems
Engineering
“V”

Component Verification

Subsystem
Verification

System
Verification

System
Validation

Operations &
maintenance

Design Commitment



Consequences of Not Doing Upfront SE

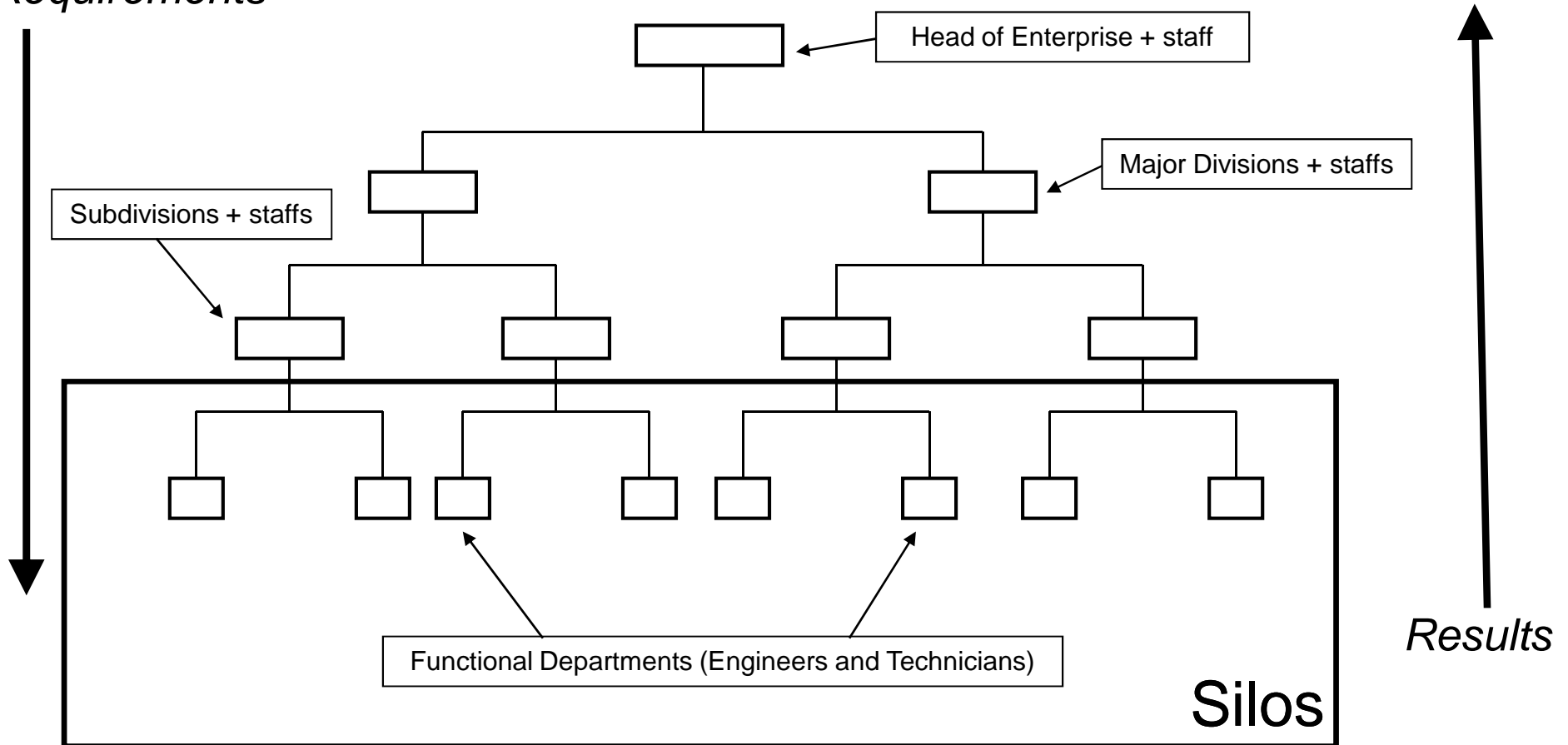
- *Impact of Simulation on the design is a lot lower than it could be*
- Problems in the design are detected late or only in the field – high added cost
- Lack of time/budget to explore multiple concepts
- Physical testing is used a lot more than it should be
- Experts become a bottleneck in the process – loss of experts becomes a serious loss of IP

Bottom Line:

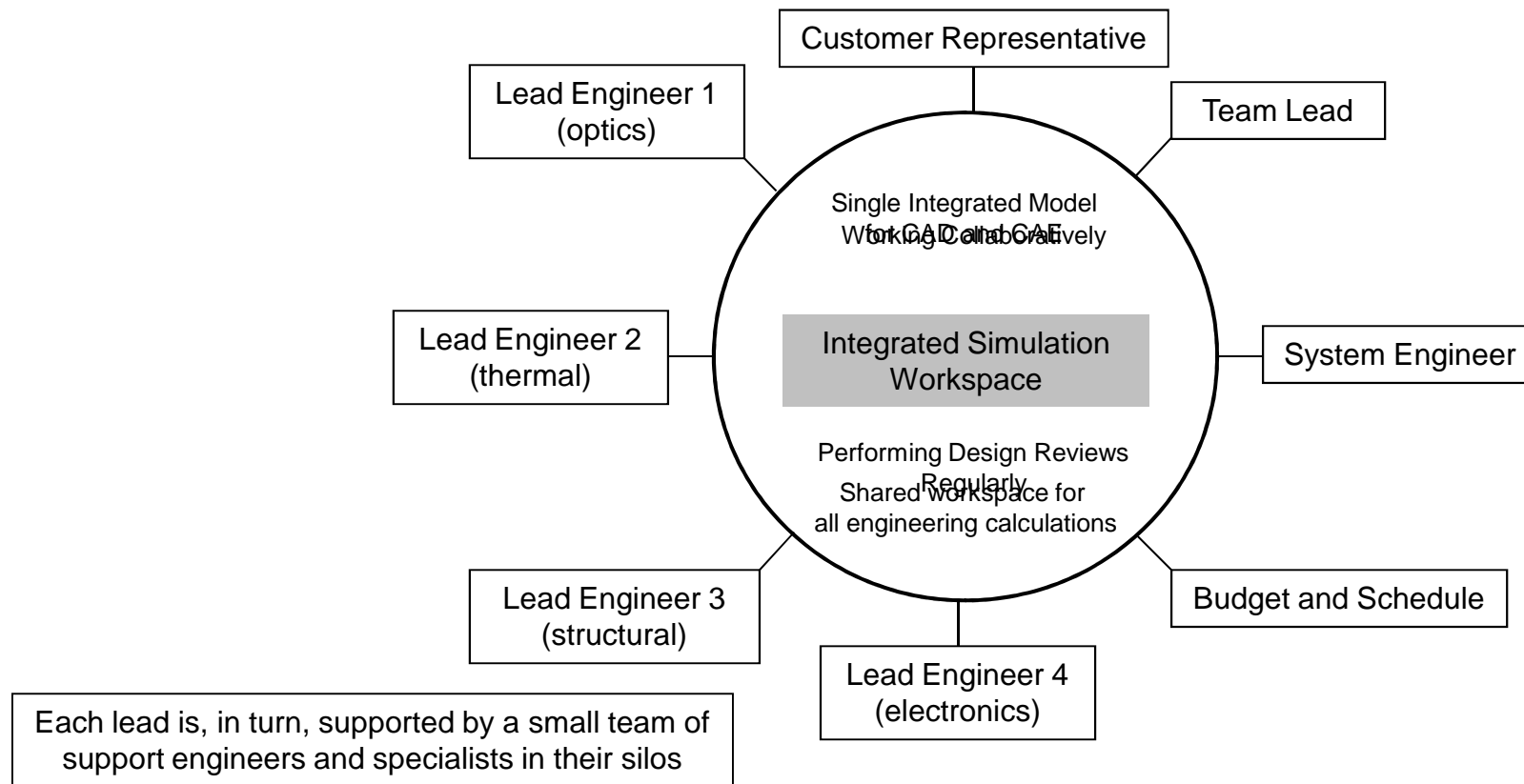
Projects consistently have huge cost and schedule overruns.

The Hierarchical “pyramid” Organization

Requirements



The Concurrent Engineering Approach



Concurrent sessions over 2-3 days were able to accomplish work that would normally span 2-3 months or more

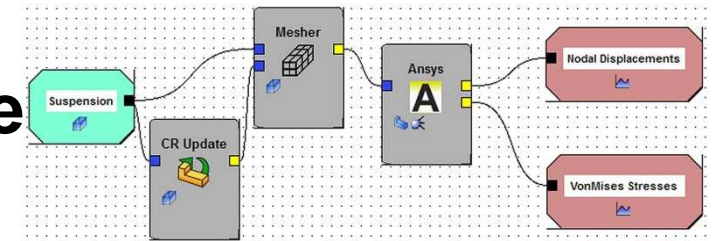
Concurrent Engineering: Software Requirements

- Effective and efficient communication of *all* the data amongst *all* team members
- “No-wait design reviews” including requirements checking (*no simulation tool expertise needed*)
- Efficient evaluation of multiple concepts and what-if trades at multiple levels of model fidelity
- Single, integrated view of all the model data (*CAD, structural, thermal, optical*)
- Effective configuration management and access to all project data including CAE models and results
- Extensible environment (for commercial and in-house tools)
- *Use of COTS CAD and CAE tools*

Comet's Performance Engineering Workspace

Performance Requirements

How does my product need to perform?
What simulation processes do I need to run and which tools will be utilized?
What are the engineering constraints?



Rapid Performance Calculations

Perform many “what if” design studies

The Comet Performance Workspace

Abstract Engineering Model™

Performance Templates

Project-Centric Collaborative Environment



Design Concepts

With or without CAD geometry

Performance Results

Instant feedback on design

Enable collaborative decision-making

Track data pedigree

SystemRequirement	Value
Launch Cost	1.31563e+07
Launch Mass	1096.36 kg
Max Temperature	487.254 K
Max Displacement	0.00101045 mm

Comet's Performance Engineering Workspace

C:/Customers/Aerospace/Project/OBA84_proj.cmtproject (Optics_Nom_NewTemps/ Trunk Stage)

File Edit Insert Tools Import View Windows Help

Project

PhysicalModel

AbstractModel

Environment

Process

Misc. Data

Project Tree: Stages

- Collaborate easily across the team
- Access/share all data and history
- Manage Performance Requirements
- Compare simulation results with Requirements
- Manage high-level Constants and Variables

Simulation Process

- Capture simulation processes
- Capture expertise and rules
- Automate iterations
- Distribute processing easily

Geometry/Mesh/Results Viewers

- Access CAD geometry of all formats
- Create complex meshes
- Visualize results from all CAE codes

Project Dashboard

System Constants

Constant	Value
L13-L16:Mass Budget	1 kg

System Variables

Variable	Value
InitialTemperature	20 degC
Load:L13_PerPad	7.2 lbf
Load:L14_PerPad	7 lbf
Load:L15_PerPad	3.2 lbf
Load:L16_PerPad	9.9 lbf
OBA_Temperature_Bottom	14 degC

System Requirements

Requirement	Value
L13-L16:Total_Mass	1.14535 kg
Optical: Best Focus - Shift from Nominal	-0.006 in
Optical: Weighted RMS under Composite Focus	0.2648
Optical: Weighted RMS under Nominal Focus	0.4166
Optical: Weighted Strehl Ratio under Nominal Focus	0.0011
Structural: Lenses:L13:Max Disp	0.000172527 in

Process Schematic: STOP Process

Thermal View

Thermal_S1

Thermal_Set5

Thermal_Set4

Thermal_Set2

Thermal_Set1

Thermal_CR

Thermal Composite Mesh

Mapped Temperature Field

Temperature Field

User Defined

Thermal Mesh

ThermalDesktop

Rad&Thermal

Excel

Sigfit

dnidT

dnidT Disturbance

Optics In

Combine Disturbances

CodeV

Optics-V2

Scene-1

BasicTopology/Entity

Structural Composite Mesh

Static

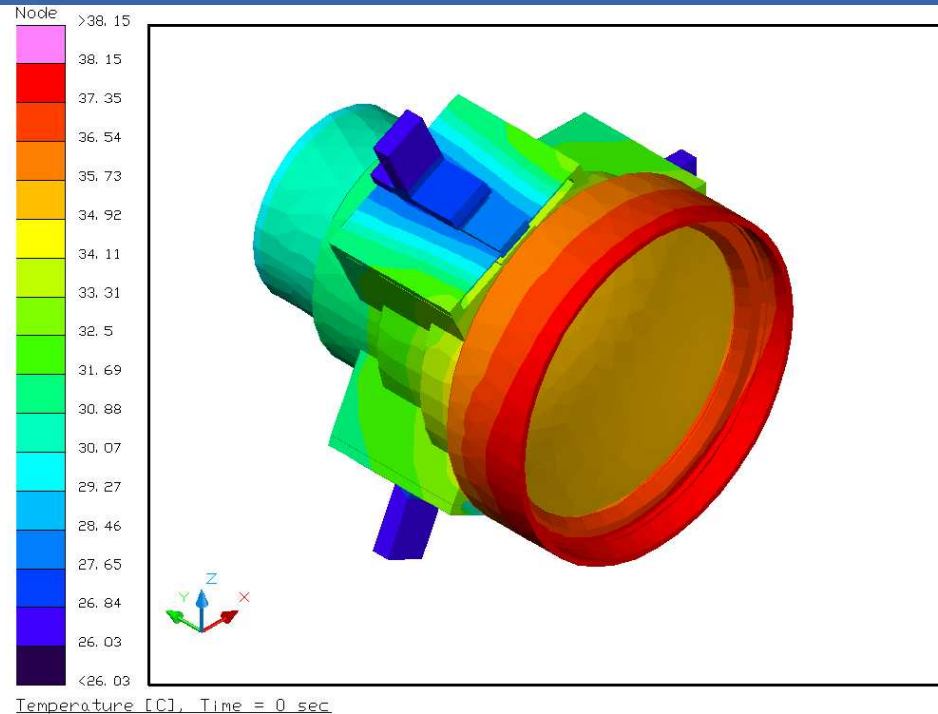
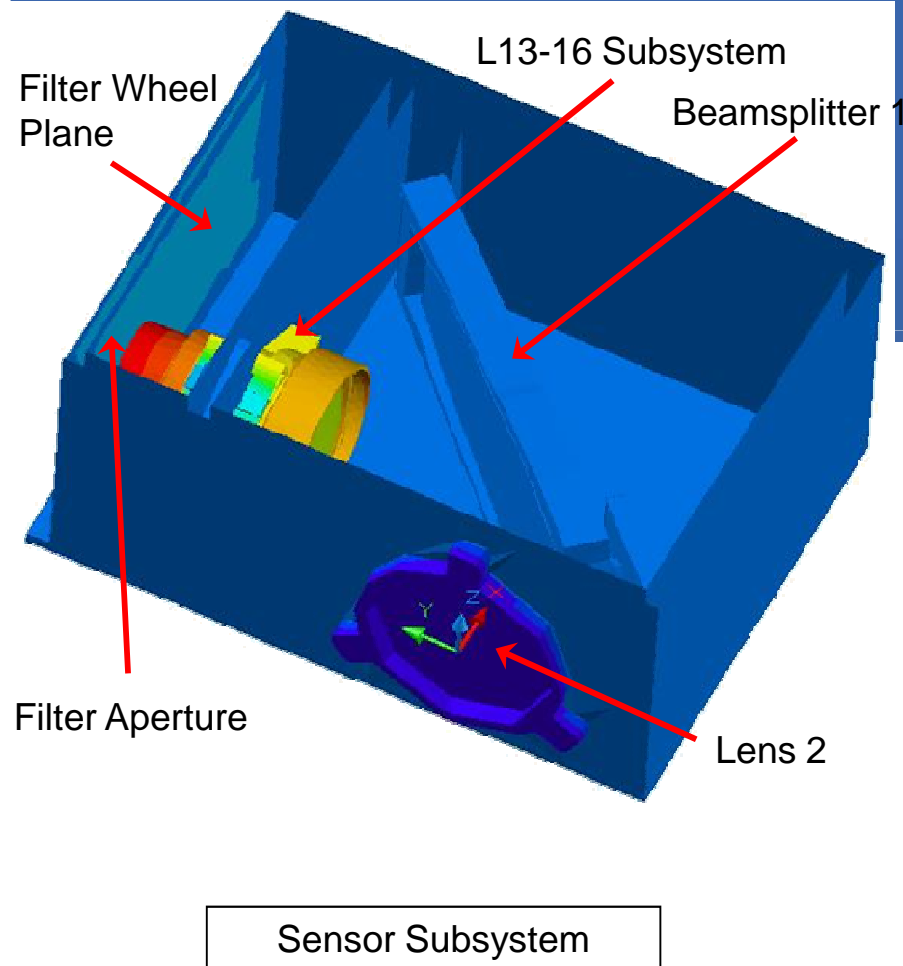
Abaqus

Static

temperatures--Temperature(degC)

13.5 18.4 23.3 28.1 33.0 37.9 42.8 47.6

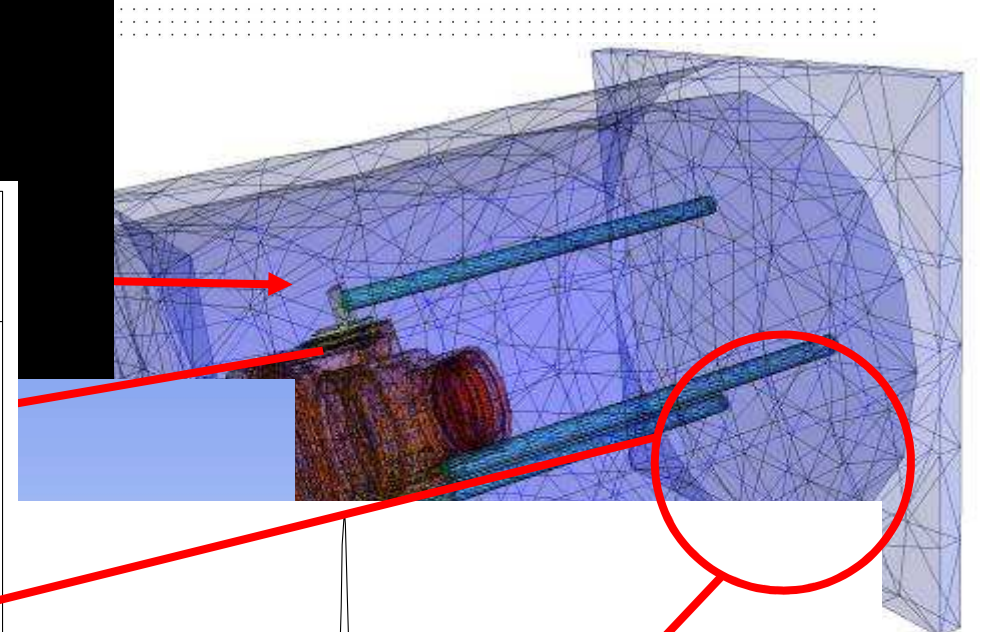
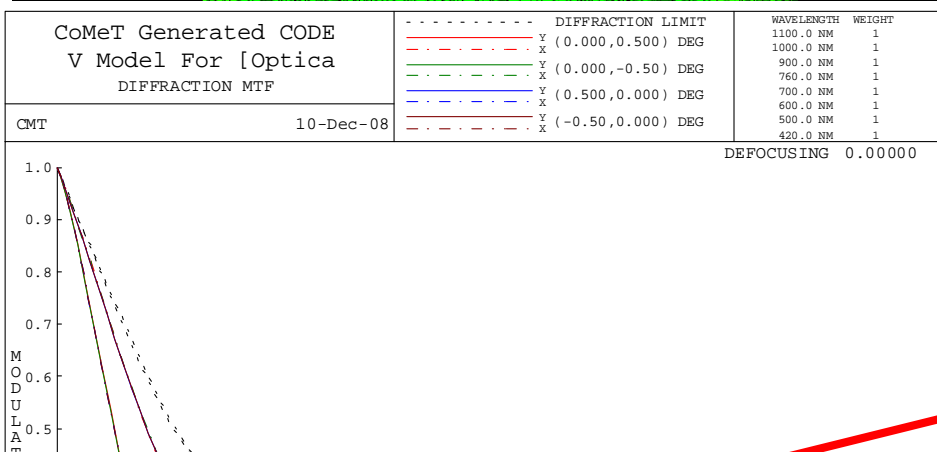
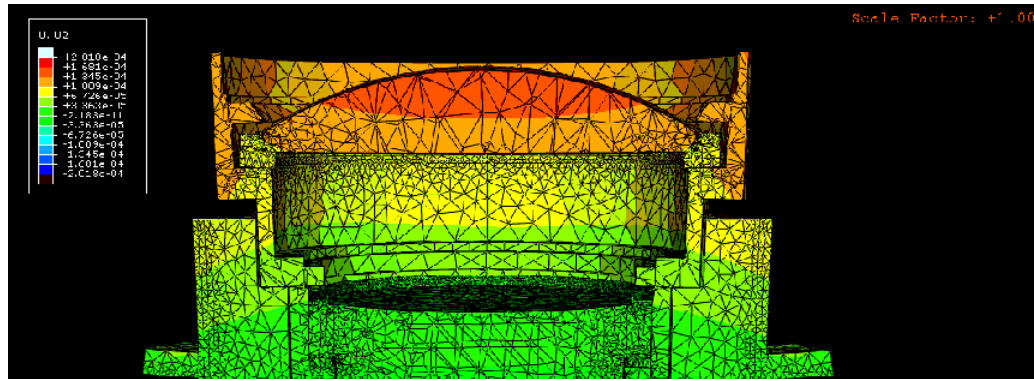
Case Study: Integrated STOP Analysis using the Comet Workspace



STOP Analysis Project – Introduction

- An independent Structural/Thermal/Optical (STOP) analysis of a critical lens subassembly (L13-16) was conducted to validate an unconventional focus control approach for a space flight payload.
- Thermal boundary condition data from final TVAC testing of the payload was used as input to determine the effectiveness of holding visible channel focus over the expected sensor thermal environment range by actively controlling L13-16 heater power .
- The STOP analyses were conducted by an engineering team from a company in the defense industry using Comet's Performance Engineering Workspace.

Performance (STOP) Process

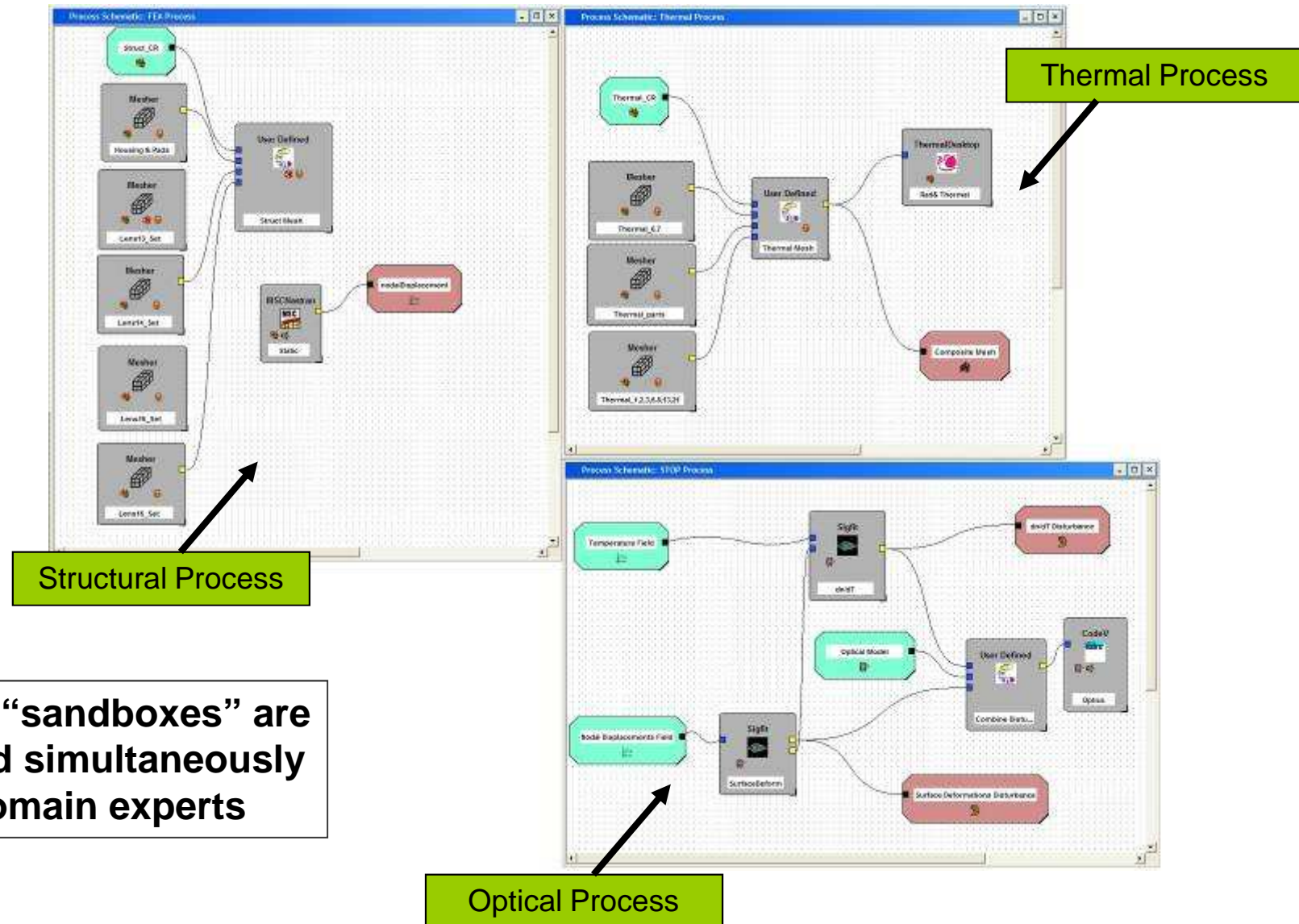


Project Dashboard

Constant	Value	Variable	Value	Requirement	Value
L13-L16:Mass Budget	1 kg	Contactor10	1550 W/m^2*K	L13-L16:Total_Mass	1.14535 kg
		Contactor11	1550 W/m^2*K	Optical: Best Focus - Shift from Nominal	-0.006 in
		Heater_L13	2.2 W	Optical: Weighted RMS under Composite Focus	0.2648
		Heater_L16	0 W	Optical: Weighted RMS under Nominal Focus	0.4166
		InitialTemperature	20 degC	Optical: Weighted Strehl Ratio under Nominal Focus	0.0011
		Load:L13_PerPad	7.2 lbf	Structural: Lenses:L13:Max Disp	0.000172527 in
		Load:L14_PerPad	7 lbf	Structural: Lenses:L14:Max Disp	8.31673e-05 in
		Load:L15_PerPad	3.2 lbf	Structural: Lenses:L15:Max Disp	0.000207164 in
		Load:L16_PerPad	9.9 lbf	Structural: Lenses:L16:Max Disp	0.000197246 in
		OBA_Temperature_Bottom	14 degC	Thermal:Temp:L13:Max	35.8942 degC
		OBA_Temperature_Sides	13 degC	Thermal:Temp:L14:Max	32.8761 degC
		OBA_Temperature_Top	14 degC	Thermal:Temp:L15:Max	30.6 degC
		Structures_InitialTemperature	40 degC	Thermal:Temp:L16:Max	30.3656 degC

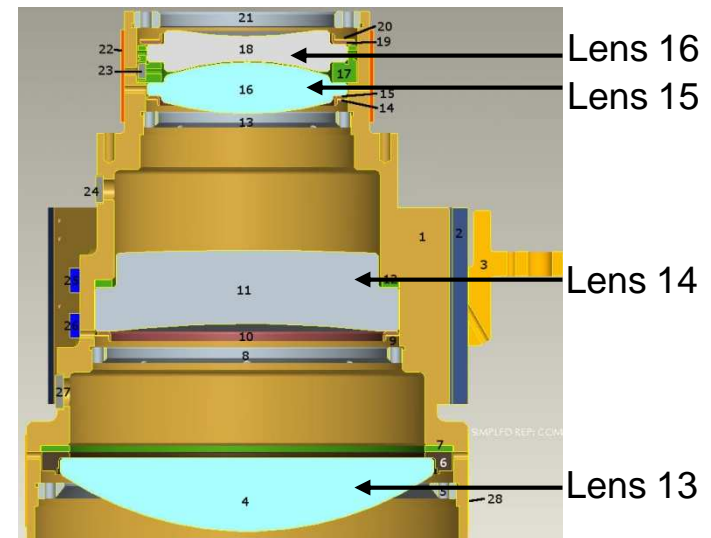
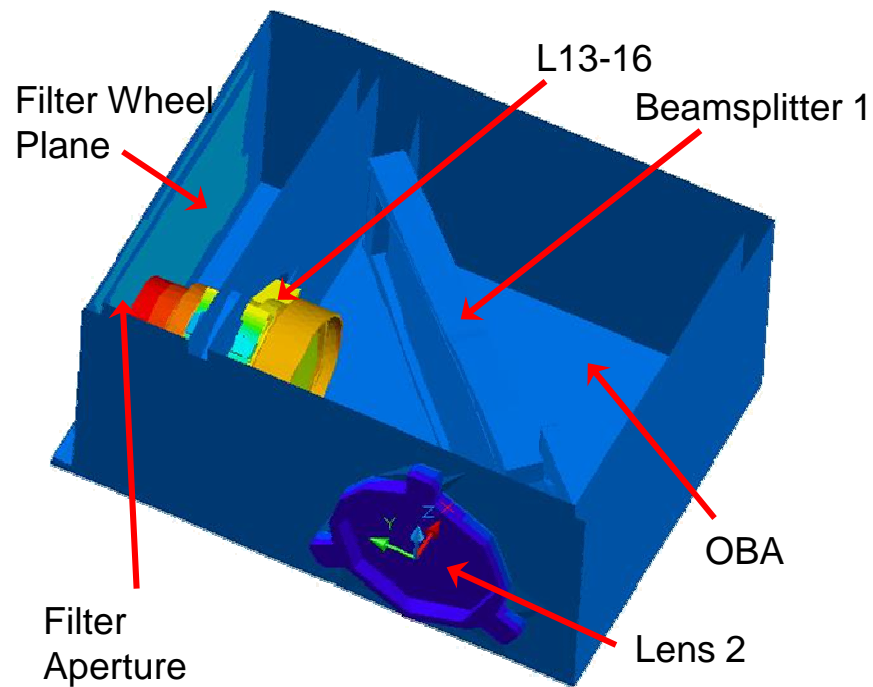
Reusable Simulation Templates

Capture & Reuse Multi-Disciplinary Processes



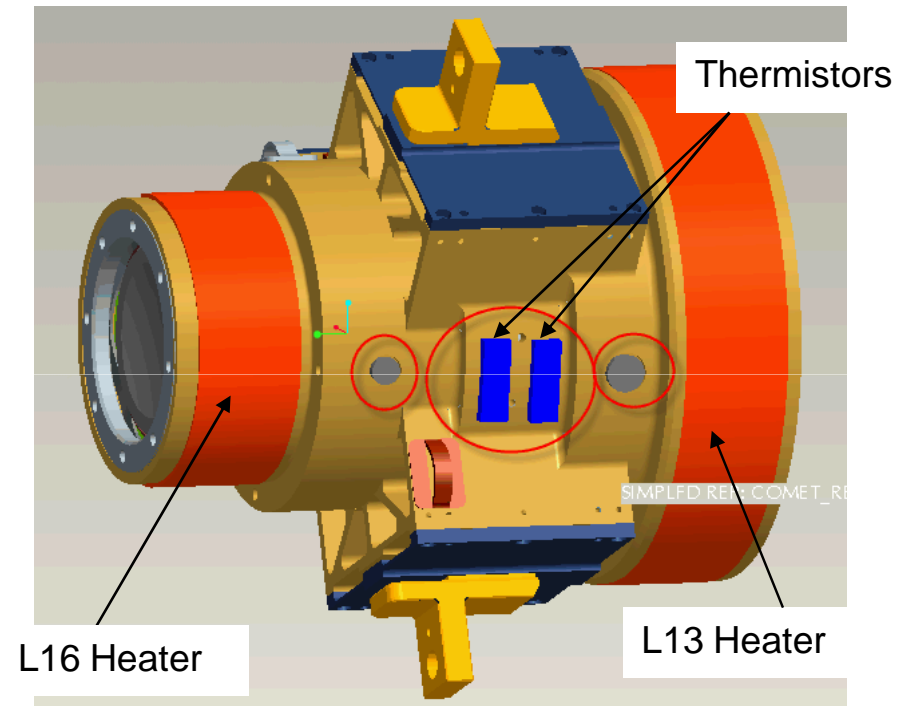
Visible Channel Overview

- A CAD model for a portion of the visible channel optical system was imported into Comet.
 - A high fidelity model of L13-16 was used.
 - A simplified, low fidelity model of the rest of the Optical Bench Assembly (OBA) was used

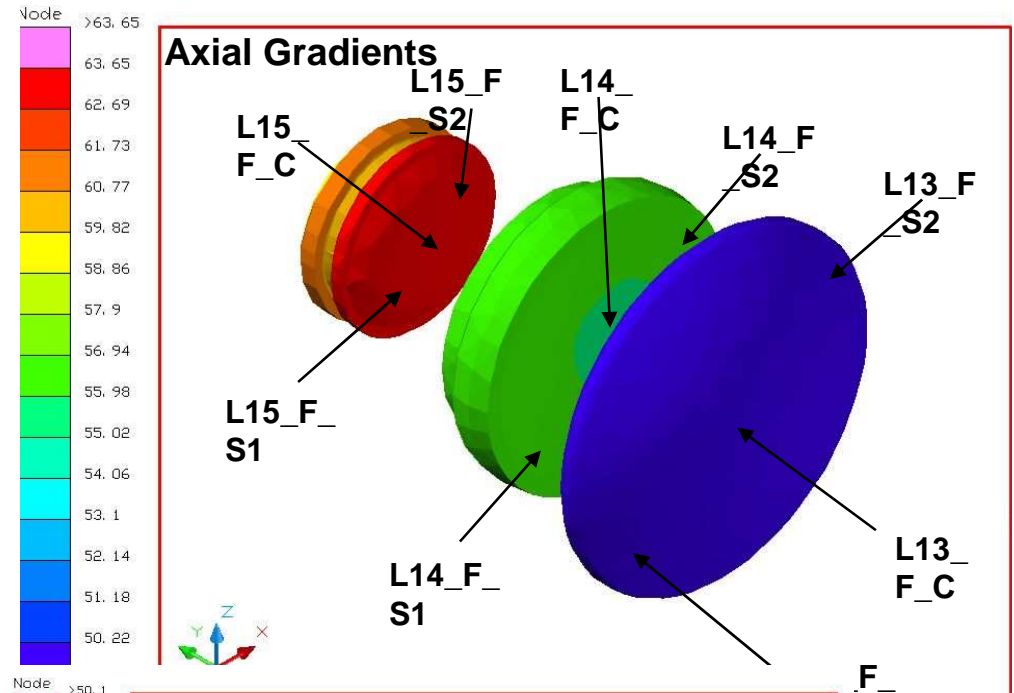
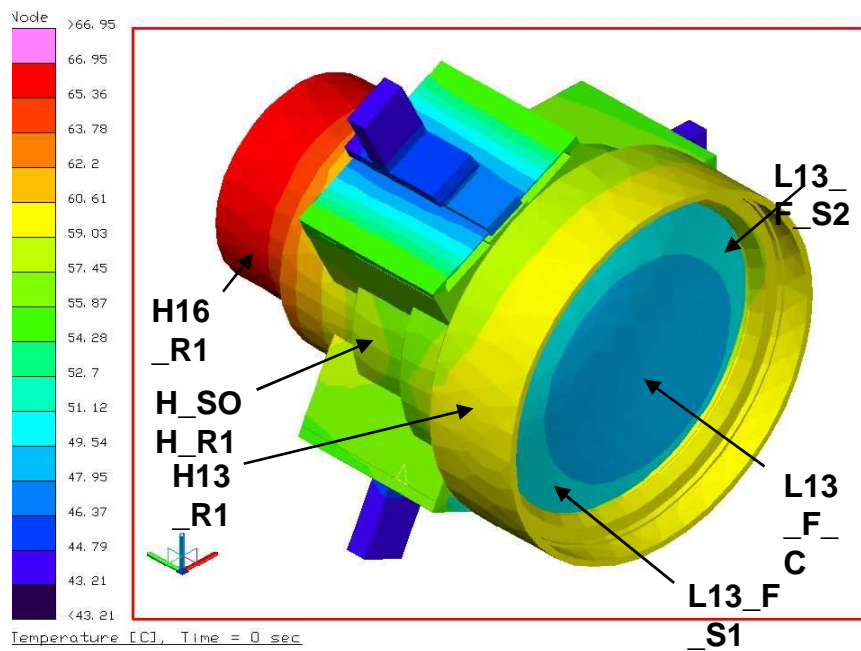


Lens 13-16 Thermal Control

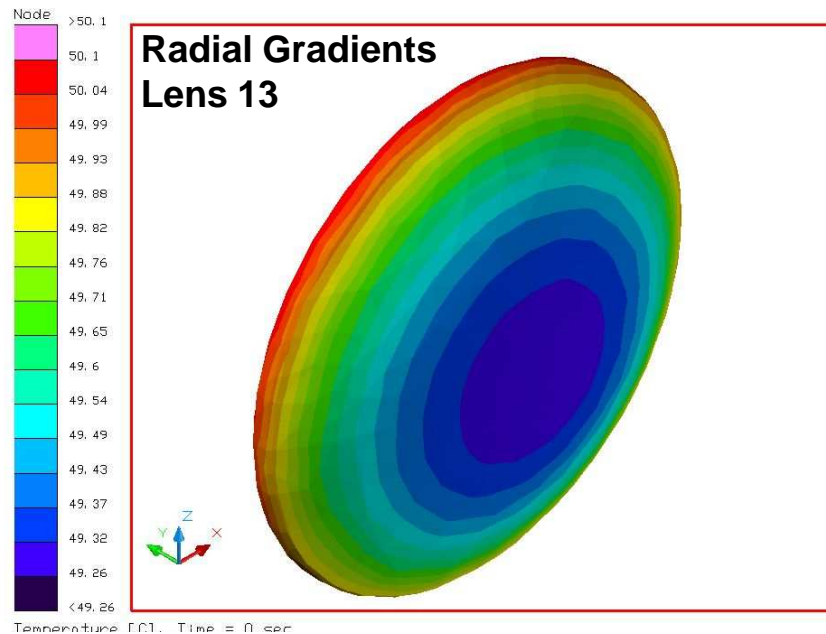
- The temperature of L13-16 is controlled by two heaters, one on the L13 side of the housing and one on the L16 side of the housing
- Although the surface area of the L13 heater is larger than the L16 heater, *equal amounts of power are supplied to each heater resulting in a much higher power density near L16*
- An axial thermal gradient is set up in the 4 lenses of the L13-16 subassembly by this thermal control approach.



Thermal Results With TC Locations

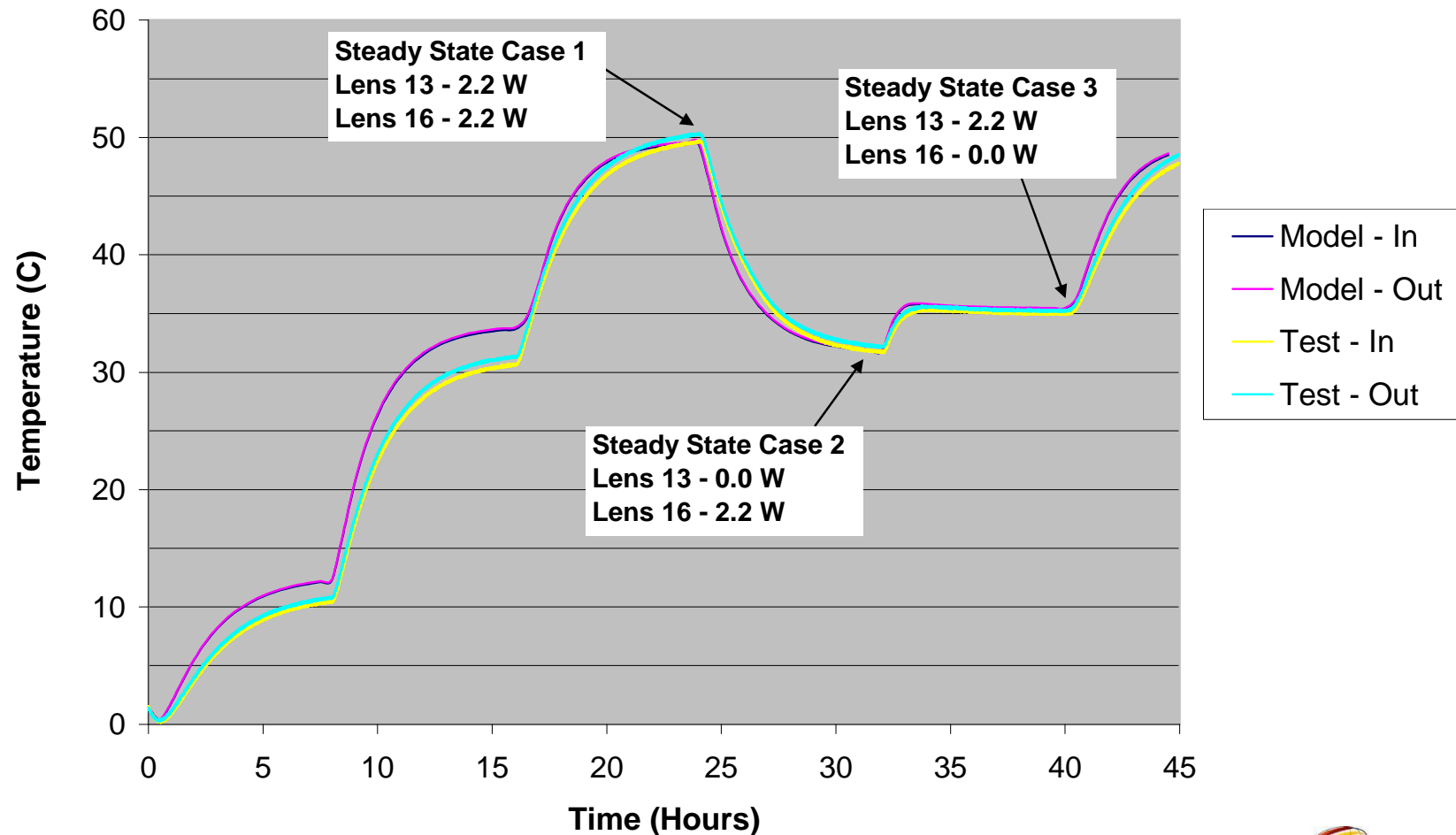


Test Condition:
L13 and L16 heaters active



Predicted Transient Thermal Response vs. Hardware Measurement

Lens 13 Center Temperature Comparison Model vs. Test Data

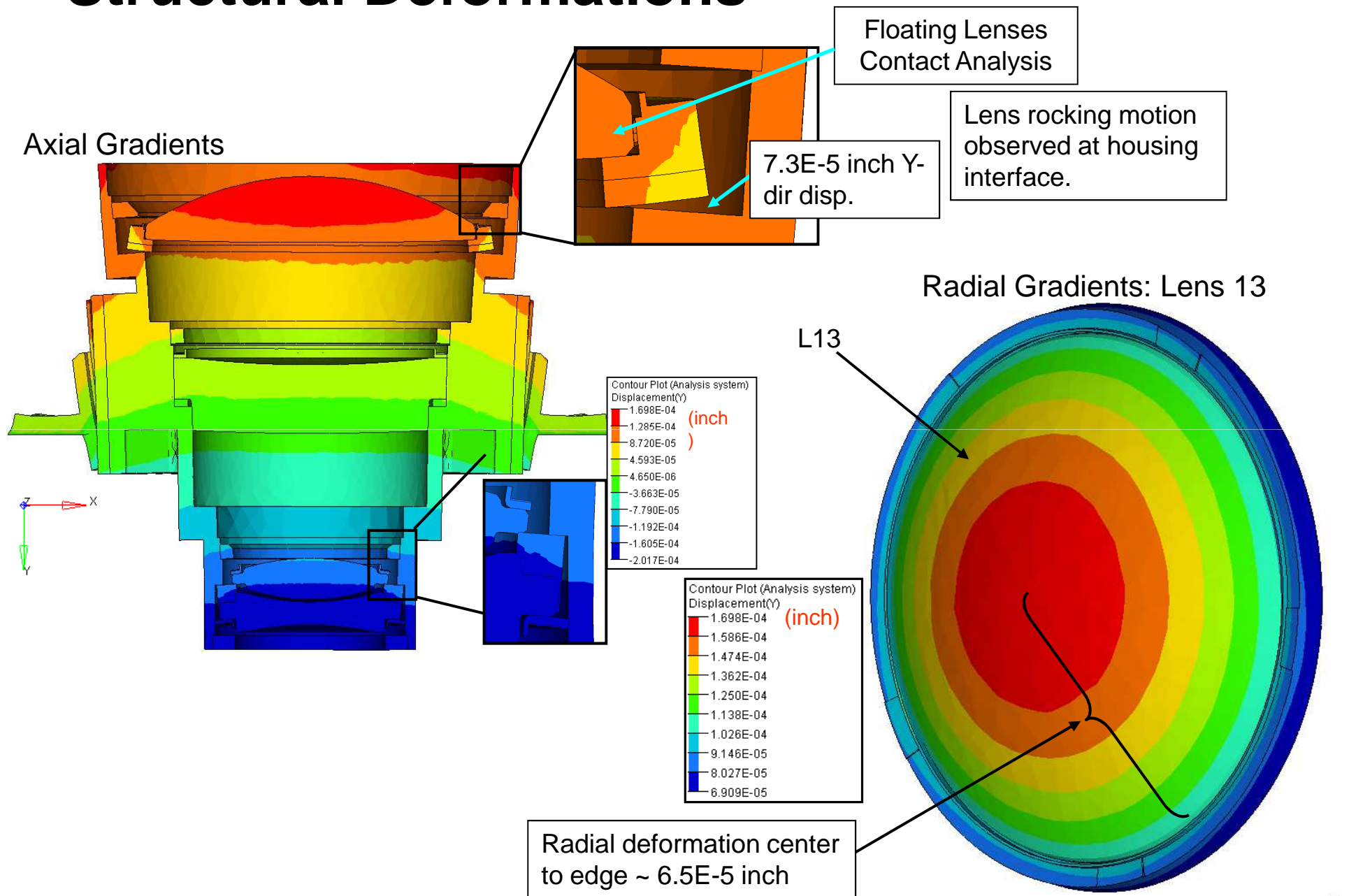


Comparison of STOP model predictions to hardware measurements (both L13-16 heaters activated)

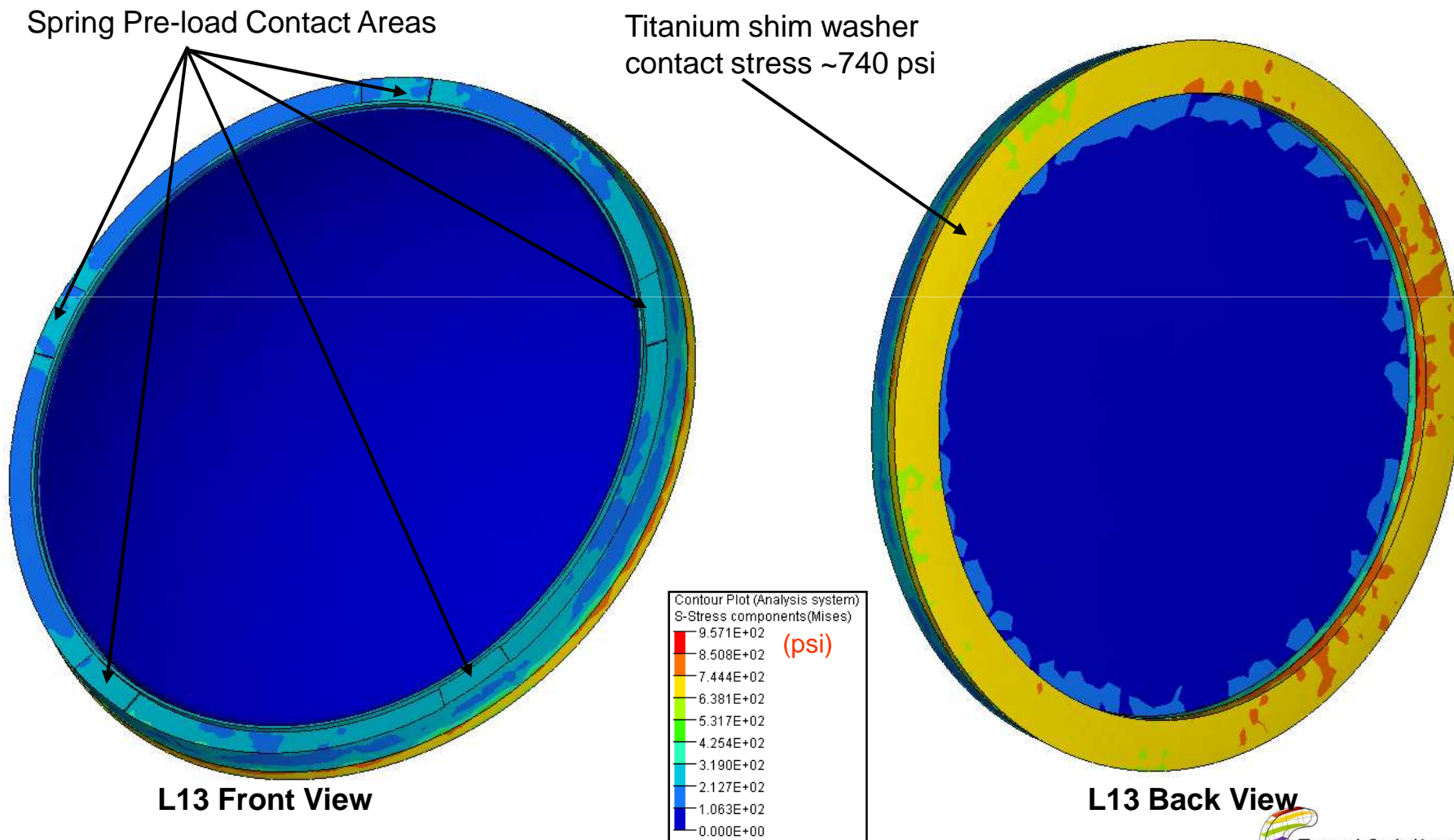
Thermocouple	Comet Model (°C)	Test Data (°C)	Comet Model ΔT
L13_F_S1	49.5	50.5	-1.0
L13_F_C	49.3	49.7	-0.4
L13_F_S2	49.5	49.8	-0.3
L13_B_S1	49.6	50.7	-1.1
L13_B_C	49.4	50.3	-0.9
L13_B_S2	49.6	50.8	-1.2
L14_F_S1	56.1		
L14_F_C	55.9	55.3	0.6
L14_F_S2	56.3	56.2	0.1
L14_B_S1	56.8	57.0	-0.2
L14_B_C	56.7	56.9	-0.2
L14_B_S2	56.6	58.4	-1.8
L15_F_S1	63.6		
L15_F_C	63.5		
L15_F_S2	63.6	61.6	2.0
L15_B_S1			
L15_B_C			
L15_B_S2			
L16_F_S1			
L16_F_C			
L16_F_S2			
L16_B_S1	58.1	52.6	5.5
L16_B_C	57.0	52.1	4.9
L16_B_S2	58.2	50.5	7.7
H_L13_R1	59.7	60.3	-0.6
H_L13_R2	59.1	51.2	7.9
H_L13_R3	59.5	57.7	1.8
H_SOH_R1	57.7	59.4	-1.7
H_SOH_R2	57.1	58.2	-1.1
H_SOH_R3	57.2	59.8	-2.6
H_L16_R1	65.9	63.7	2.2
H_L16_R2	65.8	48.7	17.1
H_L16_R3	65.8		

- Results correlate well with test data for most thermocouples
- Lens 16 predictions are higher than test results
 - Test data shows lens “center” temperature higher than “side 2” lens edge temperature - indicates “side 2” reading may be incorrect
 - L16 view to standoff mounting feet may be significant
 - Emissivity values may be slightly off
- Thermocouples H_L13_R2 and H_L16_R2 show much lower temperatures than R1 and R3
 - Model shows that gradients this large should not appear along the perimeter of the housing
 - Thermocouples may be in locations that are not as close to the heated area of the housing as expected
 - Thermocouples may not be bonded well enough to get a good reading

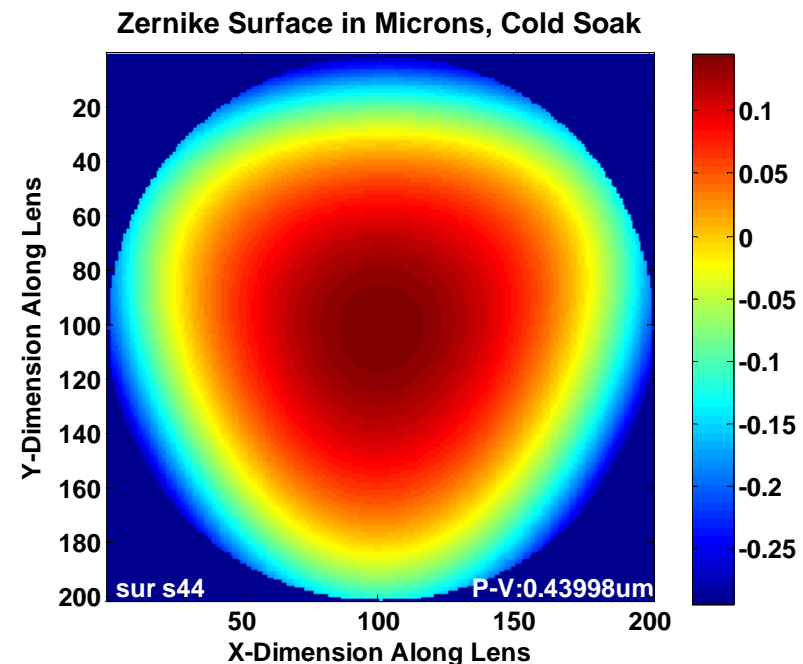
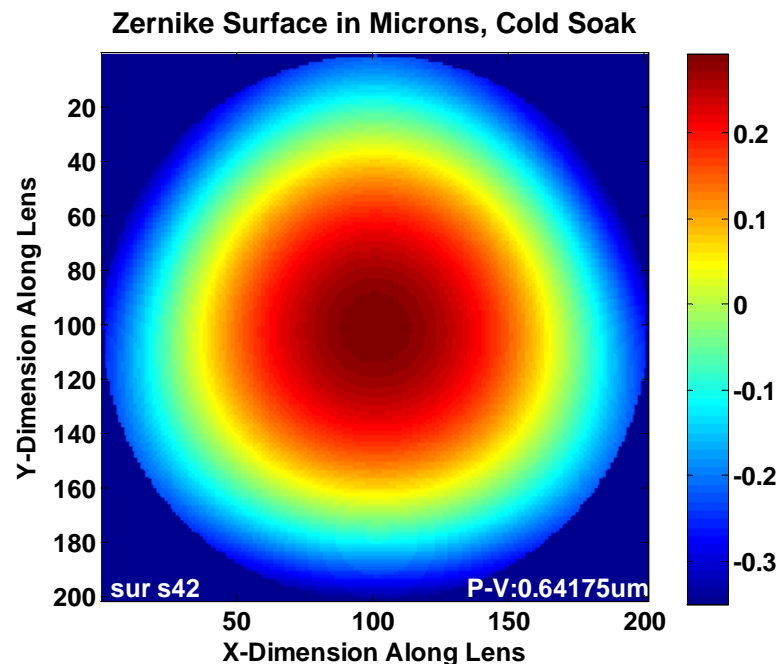
Structural Deformations



L13 – Spring Contact Von Mises Stresses



Individual lens wavefront errors due to thermally induced changes in lens surface figure – Cold Case



Wavefront error, entry surface of lens

x-decenter	S41	6.14E-05 in
y-decenter	S41	2.43E-05 in
z-decenter	S41	1.87E-04 in
a-tilt	S41	1.17E-04 °
b-tilt	S41	-2.91E-05 °
c-tilt	S41	-5.79E-04 °

Best fit rigid body
displacements of
lens surfaces
computed by
SigFit.

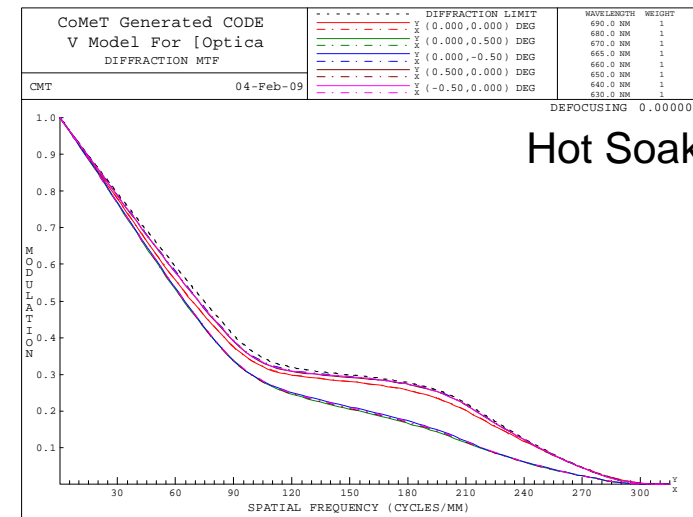
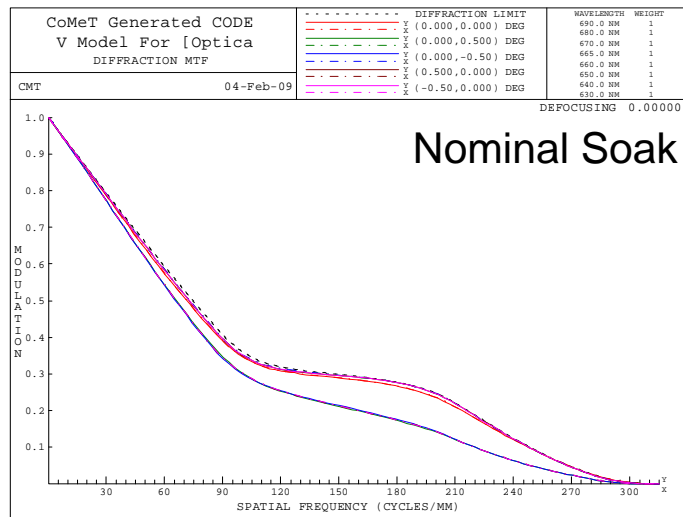
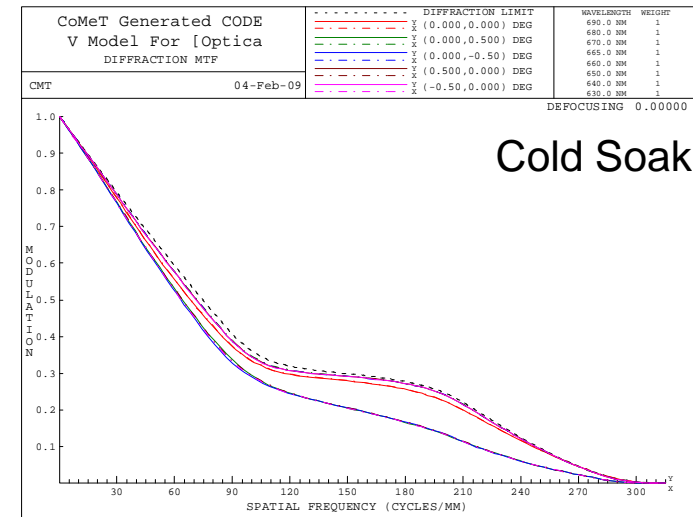
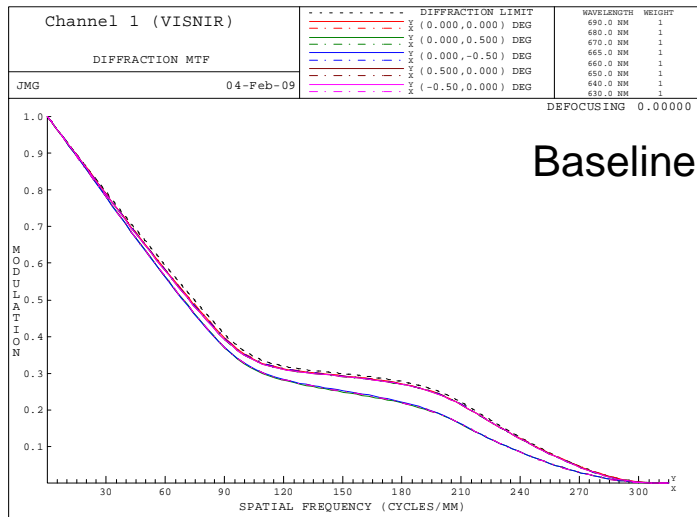
Wavefront error, exit surface of lens

x-decenter	S42	6.17E-05 in
y-decenter	S42	2.56E-05 in
z-decenter	S42	1.21E-04 in
a-tilt	S42	1.19E-04 °
b-tilt	S42	-4.23E-05 °
c-tilt	S42	-5.79E-04 °

About 2 waves of wavefront error are introduced by changes in the lens surface.



Comparison of Telescope Image Quality Baseline Design and Three Thermal Soak Test Conditions



STOP analysis shows that the lens subassembly thermal control system is effective at maintaining focus and image quality over the tested range of thermal soak environmental conditions.



STOP Project Technical Results & Conclusions

- Demonstrated seamless integration of Thermal, Structural and Optical models in a mixed-fidelity environment
- Provided real-time model predictions of visible channel focus shifts due to thermal/structural changes
- Thermal model predictions agreed well with thermal test data.
- Found that radial thermal gradients do not create significant additional visible channel focus shifts
- Found that contact stresses on the lens elements do not generate significant visible channel wavefront error
- Easily compared TVAC test results to predictions, in real-time
- Captured and tracked all analysis data and design variations
- After the template was developed and refined, *each (validated) STOP analysis was completed within a day*

Better insights into system behavior, faster STOP cycle time,
fewer errors – *and more fun working this way!*

STOP Project: Business Results & Conclusions

A New Core Capability was Demonstrated
Ability to rapidly perform High Fidelity STOP Analysis

- Achieved greater level of understanding of how changes within one domain affect other domains – systems engineering approach is facilitated across silos
- Gained greater insight into how/why the sensor design worked
 - Project Dashboard enabled visualization and team review of interdisciplinary design issues in one system-level view
- Gained higher level of confidence in the accuracy of the sensor analysis – eliminated hand-off errors between discipline silos
- STOP analysis cycle time reduced by at least a factor of 2X – *each new analysis iteration increased the savings further*
- Conducted real-time design reviews with program management and customers within the Comet Workspace without the need for separate PowerPoint snapshots of design status
 - Full system reviews, comparing predictions to requirements
 - Interactive 3-D data available for the reviews

Customer gained system insights quickly, at a much lower relative cost.

Thank You For Listening

Contact Information

Malcolm Panthaki

Comet Solutions, Inc.

505.238-1555

malcolm.panthaki@cometsolutions.com

<http://www.cometsolutions.com>

Don Tolle

Comet Solutions, Inc.

513.295.3641

don.tolle@cometsolutions.com



STOP Analysis Today – Issues

- Multiple discipline experts/tools/data in hierarchical silos
 - Manual data handoffs are inefficient and a source of errors
 - Interdisciplinary problems are difficult to detect early
- No single systems/performance view of the entire sensor – what-if trades over the entire system are difficult to execute
- System performance against requirements can be difficult to evaluate across engineering discipline boundaries
 - Data must be extracted from each silo and may not be consistent across discipline boundaries.
- Design changes result in extensive data rework for analysis
- Configuration management of all CAE models and results across the entire project is difficult.

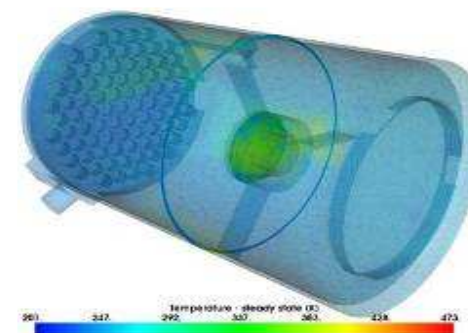
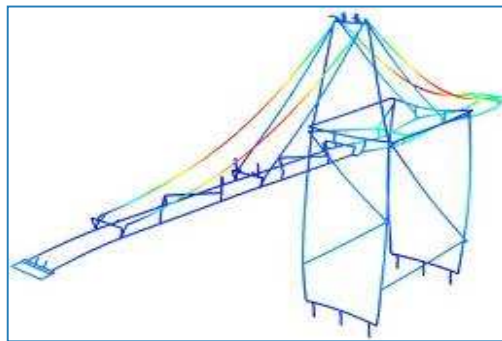
Comet Performance Engineering Workspace: Solutions for Effective Concurrent Engineering

Secret Sauce

- **Data:** Abstract Engineering Model (AEM™)
 - Single systems/engineering view of the product
 - Support for all levels of model fidelity (*not* geometry-centric)
 - Highly-extensible data model – support can cover all physics
 - Supports the definition of Abstract Models
- **Process:** CAD-Independent Templates
 - Capture expertise in templates for safe reuse across all design phases
 - Reuse the templates across a wide range of concepts (*Abstract Modeling*)
 - Automate processes safely across multiple *disciplines and multi-vendor tools*
 - Deploy Vertical Designer Applications – the *safe* democratization of CAE
- **Collaboration:** The Project View (*not* PLM)
 - Manage/track all CAE data for the entire design project
 - Share data across the teams – facilitate concurrent engineering
 - Provide a Project Notebook to annotate data and track decisions
 - Manage all model configurations and analysis results
- **System/Design Review:** The Project Dashboard
 - Provide a summary view of model variables, performance metrics and requirements
 - Evaluate and compare designs easily
 - Empowers concurrent engineering – involves all disciplines including program managers, through all the design phases

The Abstract Engineering Model™

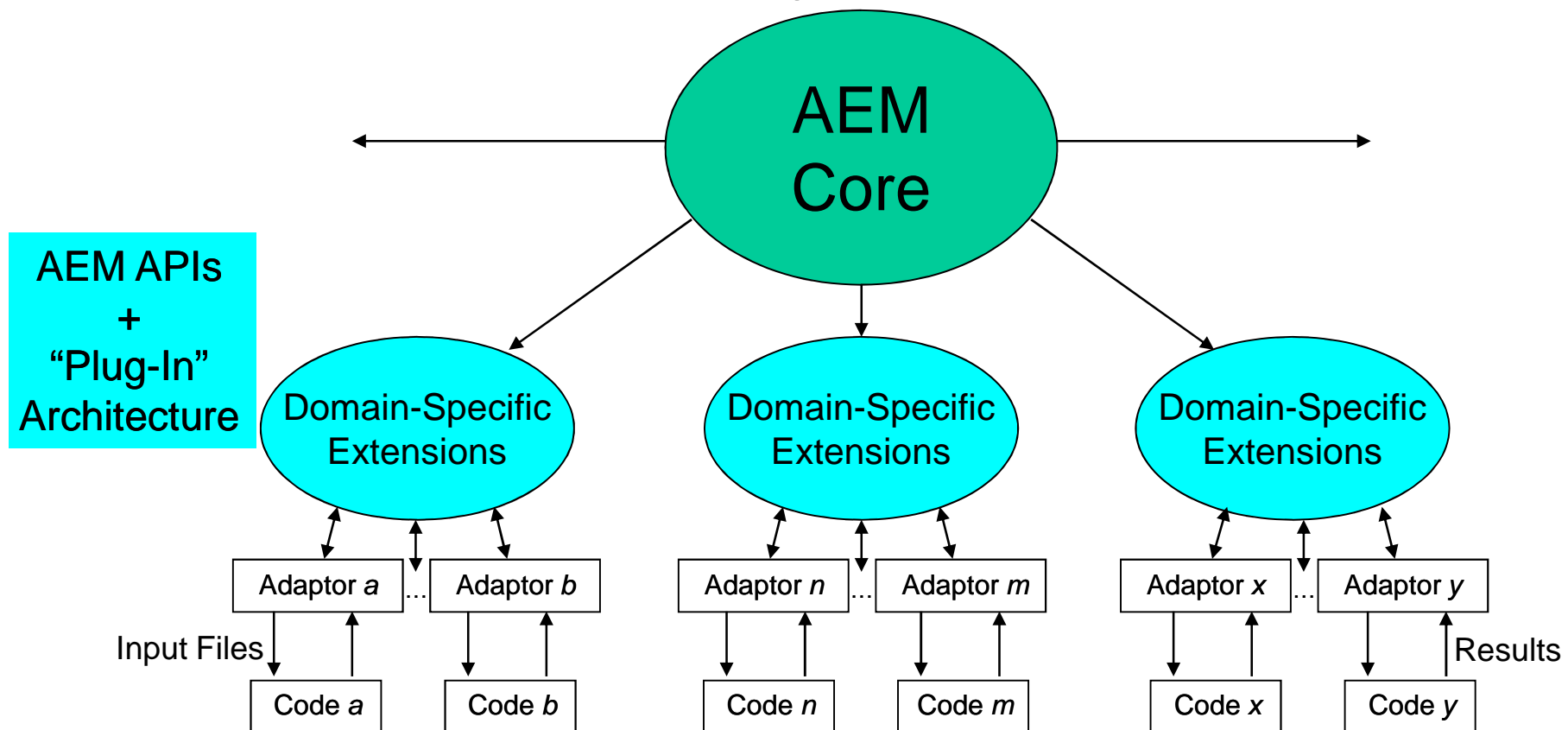
- A single, integrated data model containing design variables, functional requirements, performance metrics, models, environments, processes and analysis results
- Supports simulation templates powered by abstract modeling, providing the ability to rapidly assess widely-varying concepts
- Embraces COTS and internal/home-grown tools
- Flattens multiple environments & models into 1 conceptual model
- Eliminates manual steps & translations between domains
- Supports rapid iterations to enable good design decisions early
- *Deals with all required units and coordinate system transformations*



Automates the complexities of dealing with interrelated design and math-based simulation models to perform multi-fidelity, multi-disciplinary analysis.

The Abstract Engineering Model™

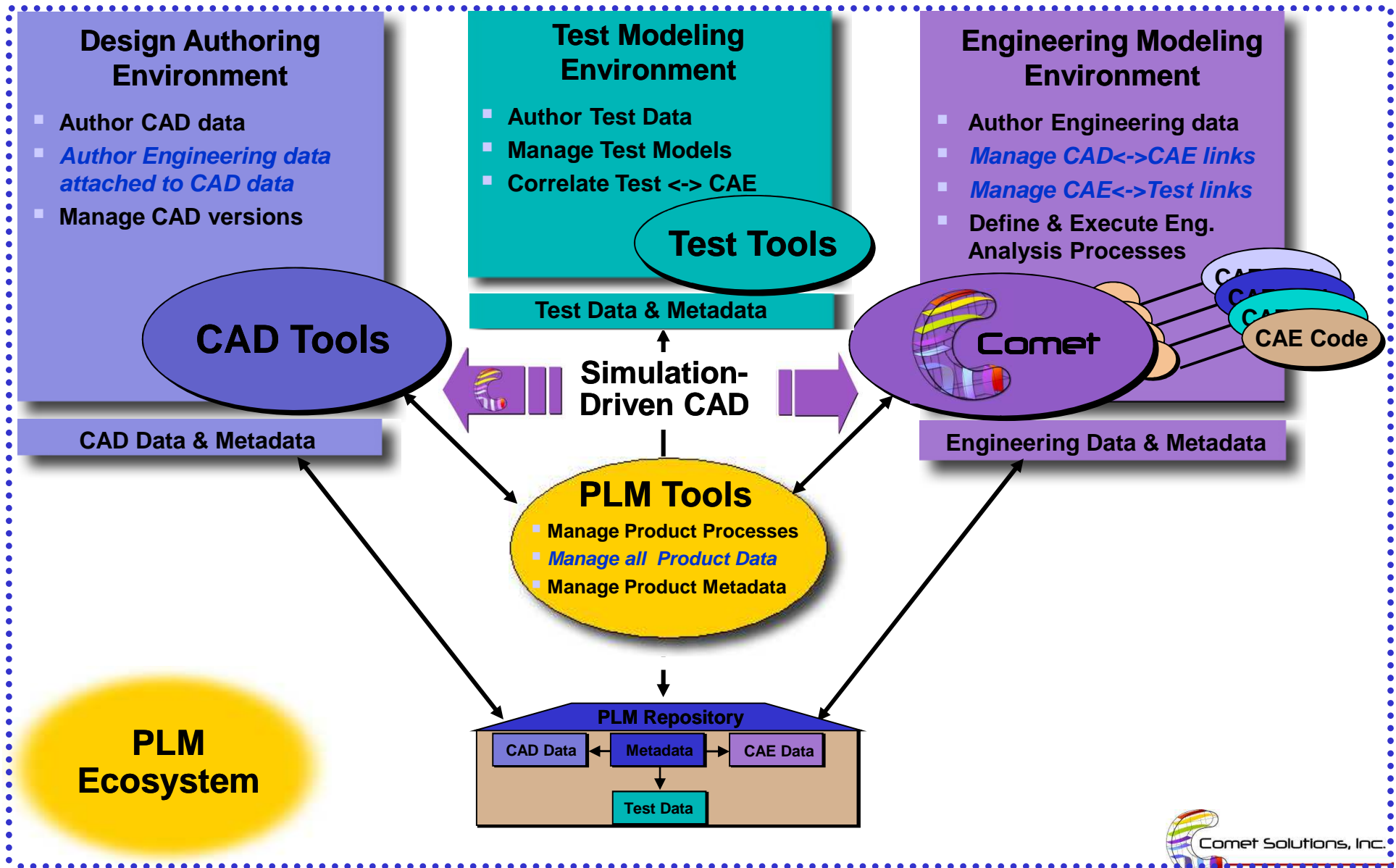
- Rigorously defined ontology that covers the spectrum of engineering analysis models from concept models to detailed 3-D models
- Highly extensible data schema: new functional component types, new physics, new analysis codes, new procedures, new environments, etc.
- Tested for >10 years: wide range of model fidelity, physics & codes



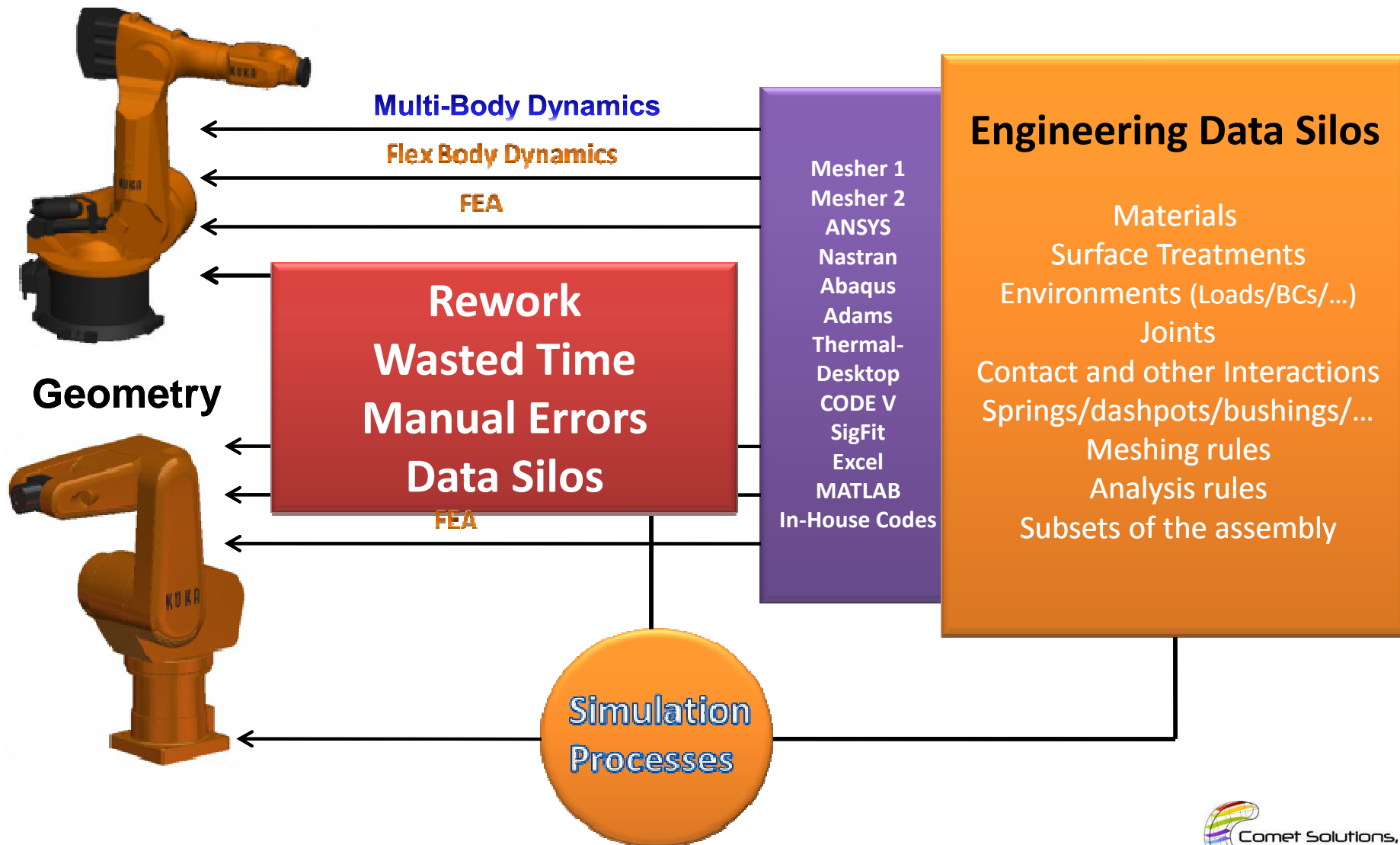
Extensibility of the Abstract Engineering Model

Adaptors	Physics	Notes
CE, SAMPLL	Weapons Analysis: Earth penetration	High-Level abstractions; No geometry or mesh Heuristics numerical calculations
Xyce, ChileSPICE	Analog circuit simulation	Lumped parameter abstractions No geometry or mesh; Huge models
Quicksilver ThermalDesktop	Electromagnetics Thermal FEA	Geometry and finite difference mesh Continuum PDE solution
CEPXS, ITS	Radiation transport	1-D FE mesh, Continuum PDE solution; 3-D with CAD geometry-no mesh:
MatLab & Excel	General purpose calculation tools	General lower fidelity mathematics and matrix-based calculations
Pro/Engineer, SolidWorks, UG NX	General purpose 3-D CAD package	Bi-directional interfaces to CAD environment
Nastran, ANSYS ABAQUS	Linear & Nonlinear FE mechanics	1-D, 2-D, 3-D including nonlinear contact support
DAKOTA	DOE, Optimization	In-house optimization developed and maintained by Sandia Labs
Code V, Sigfit, Zemax	Optics analysis	Optics abstractions (optical elements)

Comet in the PLM/SDM Ecosystem



Geometry-Centric Simulation in Silos: *The Tyranny of CAD*



Requirements-Centric Simulation: *CAD-Independent Templates*

